Deep Convection in the Ocean

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Long-term Goals

Our long-term objective is to understand how deep convection, induced by strong buoyancy forcing at the ocean surface, influences the ocean circulation through convective plumes and geostrophic eddies.

Objectives

Issues specific to oceanic deep convection are the relatively strong role of rotation, such that convective Rossby numbers appropriate to the vertical motions may fall below unity; the highly intermittent nature of the forcing, with the strong impluses coming during the passage of atmospheric weather systems; the possible highly localized occurrence of deep convection; and the subsequent spatial redistribution and mixing of convected water by geostrophic mesoscale dynamics, which arise in part from instability of the localized convection regions. Our particular research projects are computational investigations intended to (1) quantify the extent to which penetrative mixing occurs at the base of a rotating convective layer, sharpening the pycnocline and entraining denser fluid from below; (2) determine how space/time intermittency in either the surface buoyancy flux or the pre-existing ocean stratification and circulation relate to the degree of localization of deep convection; and (3) explore the circumstances under which localized convected regions are persistent after the buoyancy forcing abates or undergo erosion through subsequent horizontal mixing and restratification of the gyre interior.

Approach

High-resolution numerical simulations using the Boussinesq model developed in cooperation with our colleagues Drs. Keith Julien and Joseph Werne of NCAR are carried out on grids of 256x256x129 over domains of 2kmx2kmx1km to investigate plume-scale dynamics. Conditionally sampled composite techniques are used to isolate the plume structures. The Boussinesq model is also used at coarser resolution over domains of 50kmx50kmx2km to examine interaction between convection and simple examples of geostrophic circulation.

For more complex inhomogeneities in the initial conditions, larger horizontal domains and longer evolution times are required. Limited computational resolution then prevents resolution down to the plume scale, and a parameterization of the convective mixing is applied in these large domains (up to 200kmx200kmx4km). The use of an implicit gravity-wave Boussinesq model developed by Alistair Adcroft at MIT enables the use of longer timesteps, while representing the geostrophic adjustment process. We are studying the interaction between the vertical homogenization forced by the surface buoyancy loss and the preexisting eddy field, including the development of baroclinic instability, the horizontal homogenization of the mixed fluid by the eddy dynamics, and the possibility of persistence of isolated cores of mixed fluid, and comparing these phenomena with observations from the field program.

Work Completed

(1) We have completed a series of numerical simulations of convection forced by homogeneous cooling into a volume of fluid containing a single geostrophic, cold-core eddy, providing extensive evidence of localization of convection by anomalies in the preexisting ocean stratification. We have examined the dependence of both the

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degree of localization of the convection and the subsequent baroclinic instability on the strengths of the initial eddy circulation and stratification anomaly and on the size of the eddy relative to the deformation radius. We have performed a detailed analysis of the results, examining in particular the relative importance of buoyancy fluxes due to a secondary circulation compared to those by small scale plumes and eddies. These results are described in the article "Localization of deep convection by a mesoscale eddy" (Legg, McWilliams, and Gao) in press in Journal of Physical Oceanography.

(2) We have completed an analysis of the plume structures of turbulent convection. Plume structures are extracted from the turbulent fields associated with convection, by conditionally sampling for maxima in the downward vertical velocity, and calculating a composite plume. Using the composite to identify typical plumes we have obtained a census of the plume population and examined statistics including the amplitude, vertical tilt, horizontal radius, axisymmetry, and vertical length. The composite plume is compared with simple plume models to identify the predominant physical balances including, in particular, the relative importance of entrainment and detrainment of plume fluid and forces acting to enlarge and accelerate plumes crossing the convecting layer. The results of this plume analysis are described in an article "Plumes in rotating convection: Part I Ensemble statistics and balances", Julien, Legg, McWilliams, and Werne, submitted to Journal of Fluid Mechanics.

(3) We have developed several versions of a lagrangian particle code, to be used in investigating the response of massless particles to convective flow fields. One version, in which particles are constrained to particular vertical levels, similar to isobaric floats, has been used to investigate the response of floats to convection in the presence of mesoscale eddies. Another version, in which particles are advected by the full 3-D flow field has been used to investigate the evolution of fluid parcels in individual convective plumes, to complement the composite analysis described above. These latter results are described in an article "Plumes in rotating convection: Part II individual plume lifecycles" Julien, Legg, McWilliams, and Werne, currently in progress.

(4) We have collaborated with Ken Fischer et al. at the Environmental Research Institute of Michigan by sharing surface fields from our localized convection simulations, which they have used to simulate Synthetic Aperture Radar (SAR) images of the convecting fields. These simulations investigate the feasibility of using SAR to observe the structures of open-ocean deep convection. An article describing the results, and the feasibility assessment, "Modeled radar surface signature of deep ocean convection", K.W. Fischer, S. Legg, W.H. Munk, R. M. Shuchman, R.W. Garwood, and J.P. Palshook, has been submitted to IEEE Transactions on Geoscience and Remote Sensing.

(5) We have carried out a series of calculations of convection in the presence of mesocale eddies, where the eddies are associated with compensating anomalies in Temperature and Salinity, in addition to the density anomaly previously studied. As the flow evolves in response to surface buoyancy loss, considerable structure on a variety of scales is generated in the temperature and salinity fields.

(6) Using the implicit gravity-wave model, we are investigating a variety of convection scenarios in which the initial conditions contain a field of mesoscale eddies, with resultant interactions between the eddies determining the eventual degree of homogenization of the flow.

Results

(1) Localization of convection. Our simulations of convection in the presence of geostrophic eddies indicate that such stratification anomalies may provide a mechanism for the long-hypothesised preconditioning of the ocean for locally deeper convection. Such anomalies also provide a mechanism for restratification of the convectively mixed region, as vertical convection is replaced first by slant-wise convection, and then baroclinic instability with an associated secondary circulation. Instability eddies carry the dense fluid outwards, causing the region of deepest vertical buoyancy flux to migrate outwards. The horizontally averaged density field which results has lighter surface layers, and denser deeper layers than in that generated by horizontally homogeneous convection.

(2) Plume structures at low Rossby number. The plume structure identification algorithm allows us to examine the life cycle of a plume, from emergence from the boundary layer, through its migration across the convective layer. We compared the properties of the evolution of the typical plume vertical momentum,
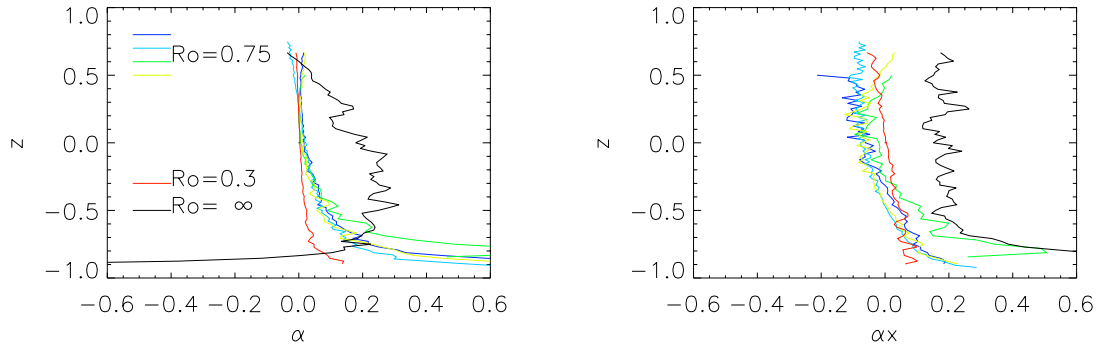
Figure 1: (a) The entrainment coefficient $\alpha = \frac{V_e}{W}$ where V_e is the entrainment velocity, and W is the vertical velocity of a plume, and (b) the mixing coefficient $\alpha_x = \frac{U_x}{W}$ where U_x is the mixing velocity and W is the vertical velocity of a plume. Entrainment leads to an expansion of a plume, while mixing modifies plume density with no volume change. Results are shown for simulations of convective plume ensembles at several different values of convective Rossby number. Note the reduction in entrainment coefficient for low Rossby number. Mixing, acting so as to cool hot plumes, remains significant.

volume, and heat content, with an idealized entraining plume model such as those summarized in Turner, 1986. Results indicate that initially entrainment leads to expansion of the plume, but this entrainment quickly ceases, and is replaced by strong mixing between the plume and environment which modifies plume properties with no change in volume (figure 1). Examination of individual plume lifecycles and the fate of particles contained within such plumes indicates that mixing events are associated with plume-plume interactions, such as mergers, filamentation and shearing, caused by the cyclonic vortices associated with the plumes.

Comparison of terms in the vertical momentum equation indicate the buoyancy force acting on the plume is largely balanced by a combination of pressure drag and momentum exchange with the environment. The resultant acceleration is therefore significantly reduced. Our solutions of strongly rotating penetrative convection (Julien et al., 1996) have previously indicated significantly less penetrative convection as the Rossby number is decreased: both increased detrainment of plume fluid, and suppressed plume acceleration are possible candidates for this decreased penetration.

(3) Simulated Synthetic Aperture Radar (SAR) fields. The simulated SAR images reveal clearly the strong shear and strain in the surface velocity fields of localised convection, associated with the generation of cyclonic vorticity in the regions converging into plume and baroclinic eddy downwelling regions. Eddies, fronts and plumes can all be identified and differentiated in these images.

(4) Behavior of floats in convecting flows. Our investigations of isobaric floats in the presence of convection localized by mesoscale eddies reveal a tendency for floats to congregate in the convergent regions associated with downwelling fronts. These fronts are associated with cooler than average fluid - hence the ensemble mean temperature measured by the floats diverges from the Eulerian mean, an important consideration when interpreting observations made by such isobaric floats. In flows with considerable eddy structure, the dispersion of floats can also reveal the process of lateral exchange and restratification.

(5) Temperature and salinity fine-structure. The addition of compensating Temperature and Salinity signatures to the eddy field provides a means of distinguishing water-masses originating from the surface, the eddy interior and the ambient flow. Within a region of approximately uniform density, fluid having its origins in these different areas may be found, leading to significant small-scale structure in the temperature and salinity fields, as a result of the incomplete nature of mixing (figure 2). For example, within an eddy generated through instability of a weakly stratified preconditioning eddy, fluid of a particular density consists of a combination of water from the preconditioned interior uninfluenced by the surface forcing, water originally from the surface made denser through the surface cooling and advected downward along a narrow front, and water from the deeper layers of the exterior fluid, upwelled in broader regions. Geostrophic eddy activity stirs these
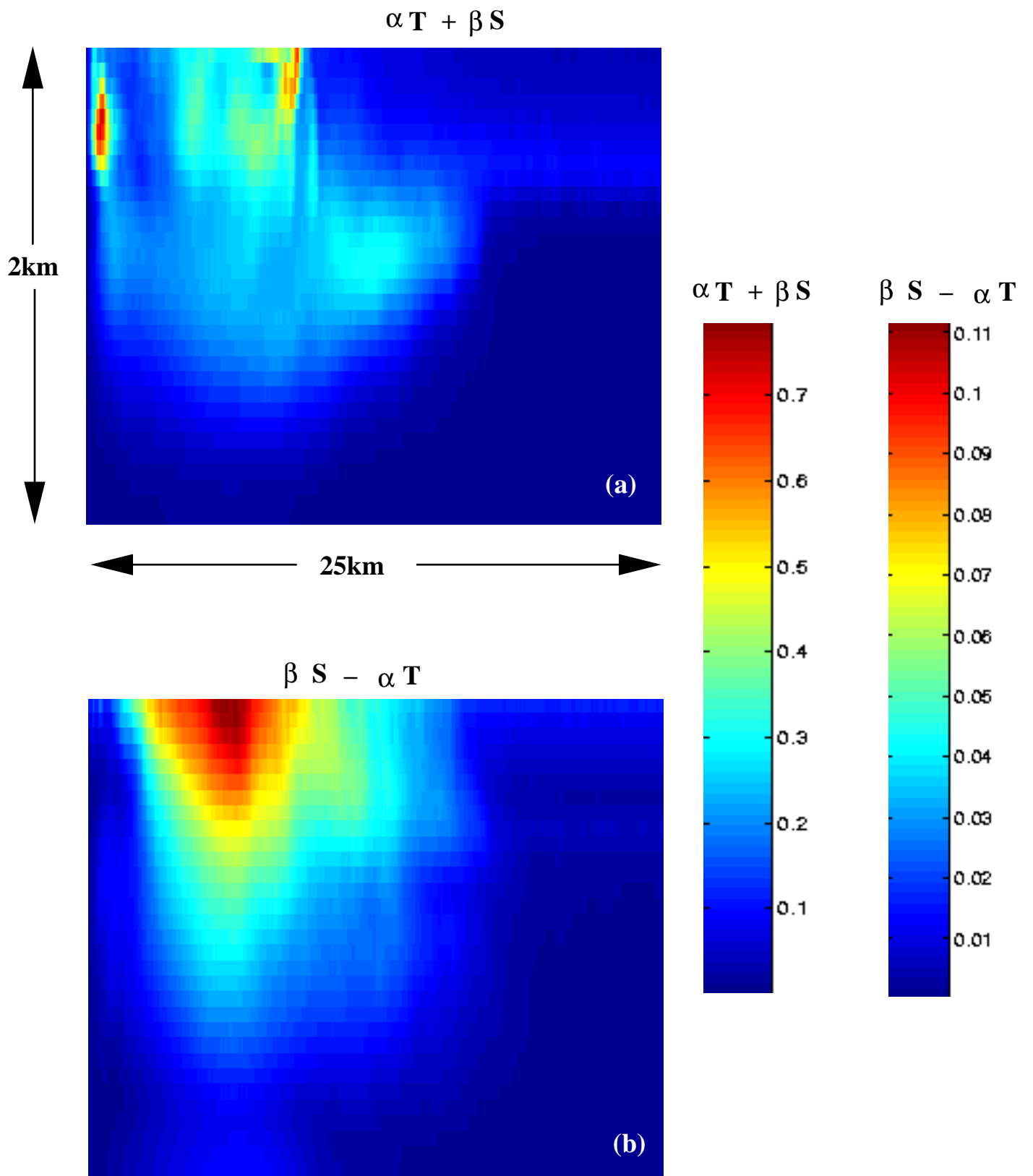
Figure 2: Root mean square values of (a) $\alpha T + \beta S$ and (b) $\beta S - \alpha T = (\rho - \rho_0)/\rho_0$ where T is temperature, S is salinity, ρ is density, ρ_0 is a reference density, α is the thermal expansion coefficient and $\beta = \partial \rho / \partial S$. The rms is defined as $X_{rms} = \sqrt{\overline{(X - \overline{X})}}$ where $\overline{X}$ is the asimuthal average of X. Fields are initially asimuthally symmetric, and are shown as a function of radial and vertical distance. A dense asimuthally symmetric eddy associated with temperature and salinity anomalies is forced by a uniform surface heat loss. Slant-wise interleaving and eddying associated with baroclinic instability lead to strong compensating variability in T and S. Hence variability in $\alpha T + \beta S$ is significantly greater than variability in $(\rho - \rho_0)/\rho_0$. Parameters are shown non-dimensionalized by the surface buoyancy loss.

different water masses together, generating interleaving filaments of each water type. The horizontal scales of variability are being compared with those noted in the observations (Pickart, private communication), and timescales for persistence of these structures estimated.

Impacts

Our research on convective dynamics should improve understanding of both the observed features of convection, and the net effects of these small-scale features on water mass transformation. This understanding provides a firmer basis for predictions of sub-polar circulations and tracer distributions and the global thermohaline circulation.

Transitions

In September 1997, Legg moved to Woods Hole Oceanographic Institution, to take up an assistant scientist appointment. Our FY1998 continuation of this grant will therefore be divided between the two institutions (UCLA and WHOI) with Legg taking responsibility for the WHOI component. Legg submitted a separate proposal for this component in August.

Related Projects

ONR Deep Convection ARI

Our simulations of convection localized by one or more mesoscale eddies provide scenarios for comparison with observations, both of the small scale velocity and temperature fields, and remote sensing signatures of the chimney scale circulation and baroclinic instability eddies. These simulations encourage the evaluation of the pre-convection eddy field for comparison with the later localised convection regions. Our plume structure analysis provides detailed statistics on plume property distributions, for comparison with data from observations.

ONR Marine Boundary Layer ARI

Our studies of deep convection driven by surface cooling overlap with studies of the oceanic and atmospheric planetary boundary layers. We are engaged in a long-standing partnership with Chin-Hoh Moeng and Peter Sullivan of NCAR, making Large Eddy Simulations of boundary-layer turbulence and comparisons with the field observations made in this program.

NSF High Performance Computing and Communications (HPCC)

Our research into the small-scale features of turbulent penetrative convection continues to provide interaction with our colleagues Keith Julien and Joe Werne, as part of the University of Colorado/NCAR/UCLA NSF HPCC Grand Challenge project.

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